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A SOLID STATE LASER FOR THE BATTLEFIELD

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ABSTRACT

The Solid State Heat Capacity Laser (SSHCL) has come to a major crossroad in its evolution as we prepare for its transition from a laser technology demonstration device in a laboratory setting, to a fully operational directed energy weapon capable of engaging live targets under actual battlefield conditions. In order to accomplish this, a fieldable prototype is needed that will allow those who would ultimately use the SSHCL in the battlefield to carry out laser performance and system operations testing in conjunction with reliability experiments. A 100 kW mobile SSHCL system is proposed to be built for this next step.

1. INTRODUCTION

The SSHCL program has made steady progress toward tactical solid state laser status over the past several years. In January 2006, the SSHCL achieved 67 kW of average output laser power for short fire durations, which equates to 335 joules/pulse at our 200 Hz pulse repetition rate. Our pulsed laser has a 500 microsecond pulse width and utilizes up to a 20% duty cycle from the high powered diode arrays. This power level was accomplished by pumping 5 ceramic YAG:Nd^{3+} slabs (laser gain media), each 10 cm by 10 cm by 2 cm thick in size (Figure 1).

This power scaling demonstration is the latest in a series of actual experiments that provide clear evidence that this solid state laser architecture can indeed produce tens if not hundreds of kilowatts of power. Power scaling is achieved by simply adding more laser gain media (ceramic YAG:Nd^{3+} slabs); the more slabs in the laser, the more output power achieved, in a linear fashion. Figure 2 is a graph that shows the output power of the laser as a function of the number of slabs used. In addition, the graph shows that increasing the duty cycle of the high powered diode arrays (going from 10 to 20% duty cycle) is another way to increase power, also providing linear scaling.

Fig. 1. 10 x 10 x 2 cm thick Ceramic YAG slabs.

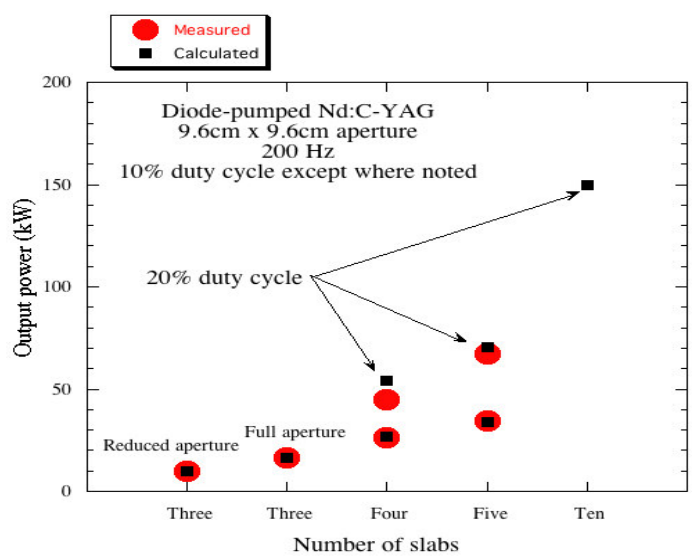


Fig. 2. 67 kW of output power achieved using 5 slabs @ 20% duty cycle

Power however, is not the only metric in determining the total performance of a laser system. Included in this discussion is the beam quality of the output laser beam as a function of laser "on time" (run time). It is accurate to say that our heat capacity architecture, where the laser gain media (ceramic YAG:Nd^{3+} slabs) stores any resultant energy in the form of heat during the lasing process and is subsequently cooled off-line as another set of laser gain media are in use, has had varied success. Until recently, local temperature gradients in the system's optical elements have resulted in the formation of higher order spatial frequencies which our adaptive optics system could not completely correct.

Recent experiments on the SSHCL have demonstrated 2X diffraction limit beam quality for up to 5 seconds of run time, roughly a 20 times improvement from our earlier performance. Equally important as these results is our expanded understanding of how and why this improved laser performance was attained; greatly increasing our confidence in scaling of the laser system itself.

Two of the main contributors to our much improved performance will be discussed. The first is the heating of optical elements in the laser cavity. Over a period of several months, the SSHCL team painstakingly tested each optical element individually. One by one, our laser beam was fired into the optical elements and monitored for temperature fluctuations by a system of thermocouples/IR camera to quantify the heating of each optical element. One optical element, namely the BK7 window (used as a cover to protect the deformable mirror from dirt and dust, Figure 3), exhibited a peak temperature rise of approximately 5 deg C per second in a very localized area (Figure 4). This steep temperature gradient was sufficient to cause wave front errors that were not totally correctable by the adaptive optics system. Replacing the BK7 window with fused silica resolved this issue and a 4X increase in run time was immediately realized.

The second significant finding was that the non-uniform pumping of the high powered diode arrays contributed to tremendous "hot and cold" areas on the ceramic YAG:Nd^{3+} slabs, creating serious higher order spatial frequencies that again, our adaptive optics system could not completely correct for. These thermal gradients were much smaller in size than the nominal 1 cm actuator spacing used in the deformable mirror, and were consequently out of the range of correction.

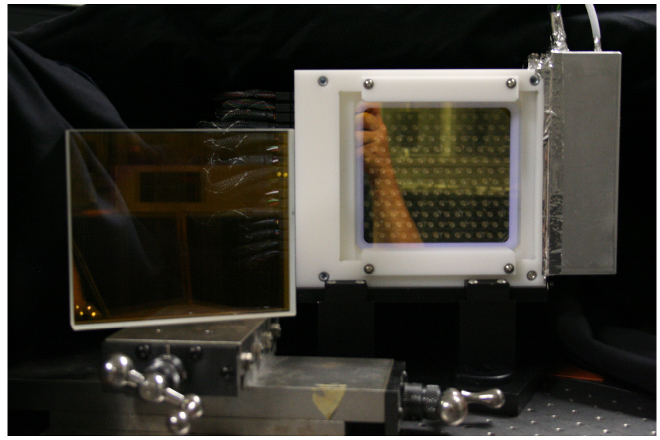


Fig. 3. BK7 window and the deformable mirror assembly

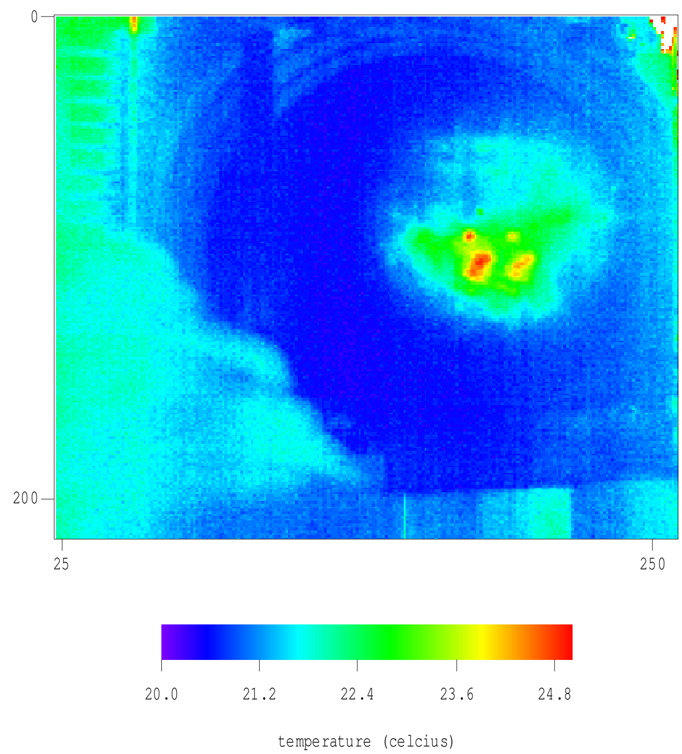
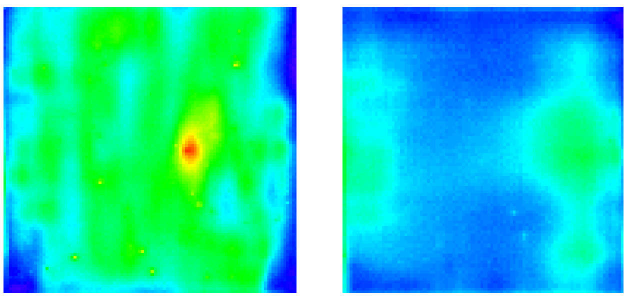


Fig. 4. 5 deg C per sec "hot spot" on the BK7 window

The SSHCL team had long hypothesized that this non-uniform pumping from the high powered diode arrays was a serious issue which adversely affected our beam quality and run time, but could not definitively prove this contention. However, we were convinced that this non-uniform pumping issue was indeed real and had to be resolved.

To experimentally verify our contention, several activities commenced. First, we characterized each and every one of the diode arrays such that we had an accurate map of how the pump light was being emitted from them. Secondly, we modeled the entire laser cavity and analyzed how the non-uniform pumping of the diode arrays contributed to the wave front error. In doing this, we developed a requirements specification for a holographic diffuser, to be placed in front of each of the diode arrays. This diffuser would basically smear the pump light on the ceramic YAG:Nd^{3+} slab and promote a more homogeneous temperature distribution on the slab. Figure 5 shows qualitatively the temperature profile of a slab with and without the diffuser.



without diffuser   with diffuser

Figure 5 Temperature profile of the ceramic YAG:Nd^{3+} without and with a diffuser

The diffuser used was an off the shelf product, and un-optimized to the pump light pattern emitted (fast and slow axis) by the high powered diode array (Figure 6). Nonetheless, the use of this diffuser over each diode array (Figure 7) proved conclusively that the mitigation of localized hot and cold regions on the ceramic YAG:Nd^{3+} contributes significantly to the reduction of higher spatial frequencies and better beam quality for increased run times.

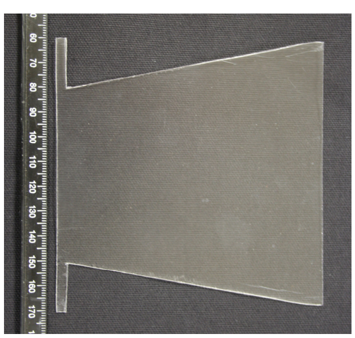


Fig. 6 Holographic diffuser

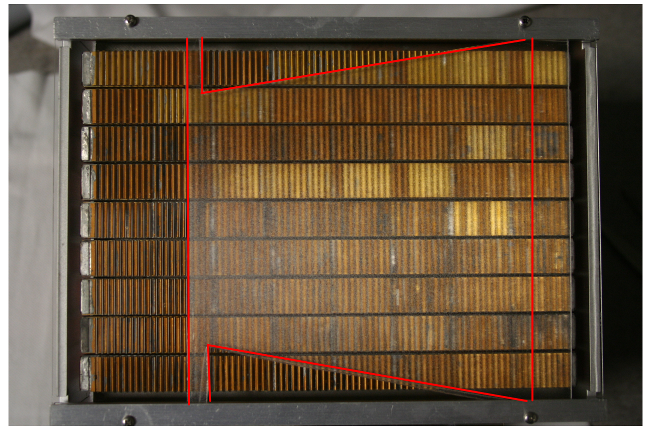


Fig. 7 High powered diode array with diffuser

The following graph (Figure 8) shows the improvement of our beam quality (BQ) as a function of run time (where 200 shots equates to 1 second of run time). We utilize the same definition of the “times diffraction limited” beam quality as defined by Northrop Grumman (Goodno et. al.) to maintain consistency for comparative purposes. As can be seen, the replacement of the BK7 window with a fused silica window improved our BQ along with the addition of the diffusers. Several runs of up to 5 seconds were completed to ensure that this result was repeatable. 2X diffraction limit beam quality for up to 5 seconds of run time has been demonstrated.

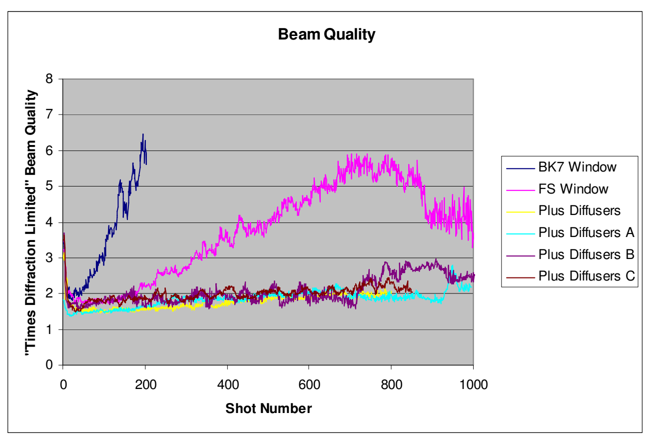


Fig. 8 “Times diffraction limit” beam quality vs. run time

With the aforementioned results, verified power scaling and significantly improved beam quality for several seconds, we believe the issue of whether the “heat capacity” concept really works, that is, that the aberrations to the laser beam can be mitigated/controlled and corrected has been put to rest.

2. 100 kW FIELD DEMONSTRATOR

The next step in the development of the SSHCL is to build a field demonstrator capable of being transported to a test range/proving ground. A series of experiments ranging from atmospheric propagation tests to the destruction of real live targets is proposed, to provide further documentation of the performance capabilities of the Solid State Heat Capacity Laser (SSHCL).

Throughout its development, the design of the SSHCL has been geared toward compatibility with the rigors of battlefield use. Our current utilization of a field-rechargeable lithium-ion battery system (Figure 9) to power the SSHCL is but one example of how the components required of a system that will see eventual field employment have been incorporated into the current laboratory device. In the battlefield, the laser must be able to sustain self-contained operation. A fully rechargeable power management system has been operating in the laboratory for 4 years that clearly demonstrates the logistics of using a battery operated laser, resolving any challenges that may be associated with this type of power source. The use of a hybrid electric vehicle, currently contemplated for use as the power source for Future Combat System vehicles, is fully compatible with our system.

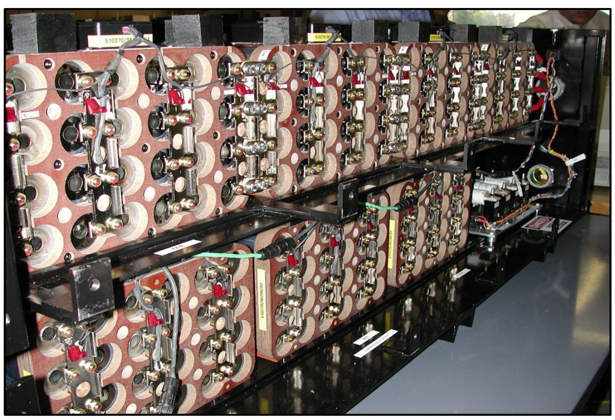


Fig. 9 Lithium-ion battery power source for the SSHCL

In addition, significant power to weight/volume reductions have been made by the manufacturer of the lithium-ion batteries over the last 4 years. A factor of 4 reduction has been achieved to date, which translates into a power system having the same input power capabilities in ¼ of the footprint, obviously enhancing the use of this type of power system for mobile applications.

For our proposed 100 kW field demonstrator, ten ceramic YAG:Nd^{3+} slabs (laser gain media), each 10 by 10 by 2 cm thick, will be placed in series to achieve this level of power performance. As mentioned previously, for our heat capacity laser technology, a slab exchange device will be used to allow one set of slabs to laze while the other sets of slabs are cooling. Figure 10 shows a prototype of a Rotating Slab eXchange (RSX) used to perform this slab exchange function.

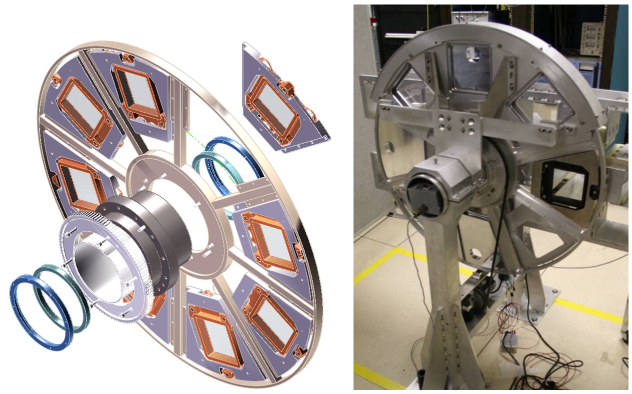


Fig. 10 Rotating Slab eXchange (RSX)
CAD model and prototype laboratory hardware

The concept of the RSX is similar to that of a Gatling Gun. For a given RSX wheel, slabs at the 3 o'clock and 9 o'clock positions are used in the lasing process. To get to the prescribed 10 slab configuration (for a 100 kW laser system), five RSX wheels are used in series, placed end-to-end at approximately a one foot spacing. The first five slabs at the 3 o'clock position are lased in series and then a two mirror system turns the laser beam 180 degrees which allows the other five slabs at the 9 o'clock position to be lased. Figure 11 shows a simplified concept, including the two turning mirrors and this "U" shaped configuration.

After 10 seconds of laser run time, all five RSX wheels are rotated one slab position in unison, allowing for a new set of ten slabs to be lased. The first set of ten slabs is now out of the laser beam path, and is cooled in real time by a series of copper cooling plates. The entire slab exchange process takes approximately ½ second for the slab rotation process to occur, and the time required for cooling the slabs after their initial 10 seconds of laser "on time" can vary between one and three minutes, depending on the type of cooling system employed.

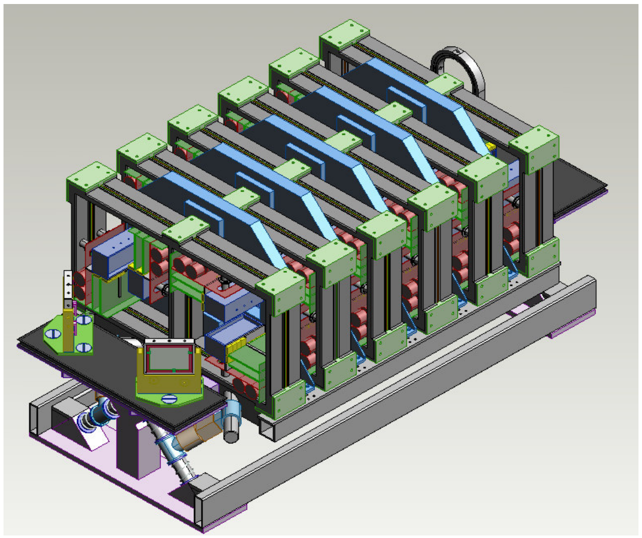


Fig. 11 100 kW SSHCL utilizing 5 RSX wheel assemblies

The above two examples are a small fraction of the type of work completed to ensure that the SSHCL can indeed be battlefield compatible. Although additional reliability and robustness tests much be conducted, both at the component level as well as the system level, these preliminary tests provide ample reason to believe that the laboratory device can be transformed into a working, field compatible prototype in a timely manner.

Many platforms for this first 100 kW field demonstrator prototype have been conceptualized. Figure 12 shows a fully self-contained 100 kW SSHCL in a movable ground-based platform. This 30 foot trailer is complete with laser, power system including recharge capability, thermal management system, operational control, and manual beam control.

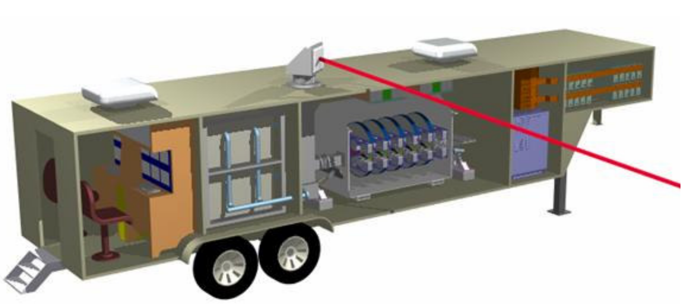


Fig. 12 100 kW fully self contained SSHCL

Additional applications for the SSHCL have prompted the need to look at a variety of different platforms, including air platforms. Figure 13 shows a fully self-contained 100 kW SSHCL in a C130 airship.

Fig. 13 100 kW SSHCL residing in a C130

A Technical Readiness Level of 7 (TRL7), "system prototype demonstration in an operational environment", is proposed for the next step in evaluating the feasibility of deploying the SSHCL in a combat theatre.

3. EXPERIMENTS USING THE SSHCL

Having a functioning laser is only a part of the total understanding in the development of a directed energy weapon. Understanding what the laser does when it interacts with a target is also required, to fully appreciate the many scenarios to which the laser system can be applied.

The Lawrence Livermore National Laboratory (LLNL) has a long history of developing laser physics modeling and simulation codes, validated by actual experiments conducted with the SSHCL. Over the last several months, many laser/material interaction experiments were conducted, using our nominal 25 kW laser system (power at the target), spot sizes up to 16 cm square, air flow speeds of 100 meters/second, with run times of up to ten seconds in duration (at our 200 Hz pulse repetition rate).

Figure 14 is a typical experimental set-up using the SSHCL. In this particular test, a large, thin aluminum sheet is the test target, with four air nozzles blowing air parallel to the target skin surface. The laser is directed perpendicular to the aluminum sheet, with a spot size of 13 cm by 13 cm at the designated 25 kW of output laser power on target. For this particular test, the laser was run for five seconds, with burn-through in about half that time.

A thermocouple attached to the backside of the aluminum sheet provided a record of temperature vs. time information. In addition, reflectivity measurements were conducted as a function of time, to allow for full characterization of the laser beam/material interaction.

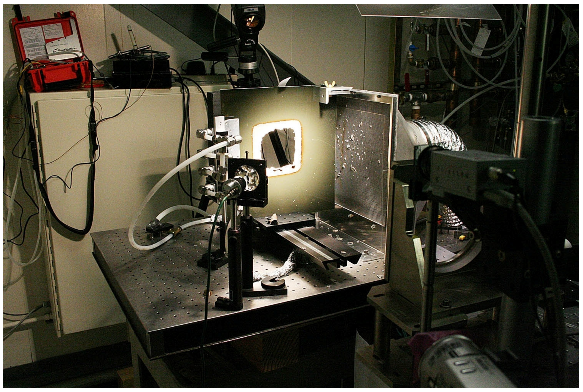


Fig. 14 Typical experimental setup using the SSHCL:
25 kW on target, 13 cm spot size,
100 meter/second air flow,
200 Hz pulse repetition rate

A much more comprehensive discussion of the high-powered lethality testing and modeling capabilities utilizing the SSHCL is discussed in a companion paper.

4. CONCLUSIONS

The development of the SSHCL has been ongoing for several years. We believe we have demonstrated the functional utility of this laser architecture and its corresponding performance. However, to take that important next step, the SSHCL must be taken from a laboratory device to a field demonstrator. A 100 kW field prototype of a mobile SSHCL is proposed.

5. ACKNOWLEDGEMENT

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